INL/CON-06-01157
PREPRINT

Correlating Laboratory Observations Of Fracture Mechanical Properties To Hydraulically-Induced Microseismicity In Geothermal Reservoirs

31st Workshop on Geothermal Reservoir Engineering

Stephen L. Karner

February 2006

PROCEEDINGS, Thirty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30-February 1, 2006
SGP-TR-179

CORRELATING LABORATORY OBSERVATIONS OF FRACTURE MECHANICAL PROPERTIES TO HYDRAULICALLY-INDUCED MICROSEISMICITY IN GEOTHERMAL RESERVOIRS

Stephen L. Karner

Idaho National Laboratory
PO Box 1625, Mailstop 2107
Idaho Falls, ID, 83415, USA
e-mail: Stephen.Karner@inl.gov

ABSTRACT

To date, microseismicity has provided an invaluable tool for delineating the fracture network produced by hydraulic stimulation of geothermal reservoirs. While the locations of microseismic events are of fundamental importance, there is a wealth of information that can be gleaned from the induced seismicity (e.g. fault plane solutions, seismic moment tensors, source characteristics). Closer scrutiny of the spatial and temporal evolution of seismic moment tensors can shed light on systematic characteristics of fractures in the geothermal reservoir. When related to observations from laboratory experiments, these systematic trends can be interpreted in terms of mechanical processes that most likely operate in the fracture network. This paper reports on mechanical properties that can be inferred from observations of microseismicity in geothermal systems. These properties lead to interpretations about fracture initiation, seismicity induced after hydraulic shut-in, spatial evolution of linked fractures, and temporal evolution of fracture strength. The correlations highlight the fact that a combination of temperature, stressing rate, time, and fluid-rock interactions can alter the mechanical and fluid transport properties of fractures in geothermal systems.

INTRODUCTION

Earthquake seismicity associated with natural fault systems exhibits a variety of characteristics that are beneficial in terms of understanding the mechanics of crustal deformation. These properties are useful for studies related to Earth structure and composition (e.g. Kellogg et al., 1999), understanding the nature of the earthquake hypocentral region (e.g. Wald and Heaton, 1992), and determining earthquake size versus event frequency (e.g. Pacheco and Sykes, 1992) - to name but a few.

Of major interest to those studying earthquake mechanics is the observation that seismicity and deformation on tectonic faults tends to repeat over time (akin to repetitive stick-slip from laboratory experiments). Several models were developed (e.g. Kostrov, 1974; Kanamori and Anderson, 1975) in an effort to define the limits of energy released during seismic events (stress drop). However, the models made basic assumptions that do not capture the complexities of nature (e.g. non-uniform slip distributions, variable stress and strength states). One fundamental observation from seismic moment data of natural earthquakes is that stress drop tends to increase as time since the last earthquake rupture increases (Figure 1). Taking stress drop as a proxy for fault strength, then this suggests faults regain some of their strength during the interseismic period.

Many of the parameters that influence the temporal behavior of fault strength have been investigated via laboratory experiments (see Marone, 1998, for a review). Results from laboratory tests are increasingly being compared to natural seismicity in our attempts to understand the mechanics of deformation along tectonically active faults (e.g. Peng et al., 2005). When applied to enhanced geothermal systems (EGS), a cursory analysis of acoustic emission patterns obtained from laboratory fracture experiments (e.g. Lockner et al., 1991) appear similar to the microseismic clouds of stimulated EGS fields (e.g. Fehler et al., 2001). This is, perhaps, not surprising as fractures in geothermal systems are of a size bridging the scales offered by the laboratory and natural faults. This suggests that a variety of results from laboratory experiments may help understand the evolution of fracture networks in EGS reservoirs. This paper serves to highlight some results from laboratory experiments that may correlate to details extracted from seismic moment tensor analysis, with particular attention to results most pertinent to the study of geothermal systems.

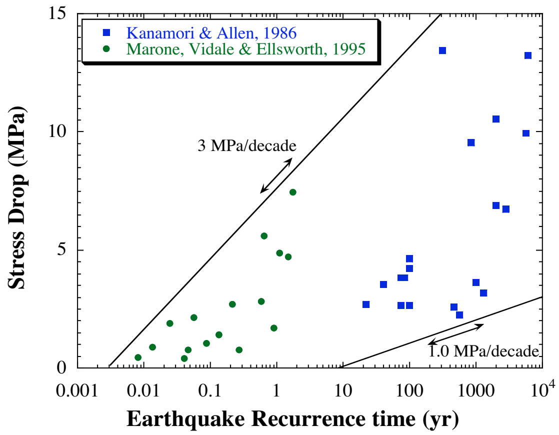

Figure. 1. Seismic stress drop for earthquakes (determined from moment-magnitude data) as a function of time between successive events. Two data sets are shown: 1. Global compilation from large crustal earthquakes (excluding subduction events; after Kanamori and Allen, 1986), and 2. Compilation from repeating earthquakes on the Calaveras Fault, California (after Marone et al., 1995). Data are bound by envelopes suggesting that earthquake stress drop increases ~1 to 3 MPa per decade of recurrence time.

LABORATORY OBSERVATIONS

Mechanical closure of Mode I cracks

When engineering geothermal systems, it is often assumed that the stimulating fluids act to generate Mode I (opening) tensile fractures. Yet, in detail this assumption appears too simplistic. Recent analyses of seismic moment tensors at the Soultz EGS site show that non-double-coupled seismic sources (indicative of mode I, tensile failure) are primarily found near injection wells (Cuenot et al., 2005). Far from the injection wells, the seismic moment tensors appear to have a double-coupled source indicative of shear failure (although, deformation might occur via a combination of tensile and shear failure). Such a spatial transition from tensile to shear (or even mixed-mode) fracturing is consistent with laboratory-based studies assessing the interactions between mode I tensile cracks (e.g. Healy et al., 2005).

When fluid pumping is stopped (e.g. at shut-in) the injected fluid is allowed to drain through the reservoir with a portion of fluid returning to the injection well. Draining serves to lower the fluid pressure which, in turn, raises the effective pressure normal to the fractures. The forces associated with increased effective pressure will inhibit shear and close open fractures. During closure, any asperities on fracture walls will contact the opposing walls and help prop the fracture open. Should the asperities succumb to brittle failure or time-dependent creep, the fracture apertures will decrease further – potentially reducing the interconnected void space required for fluid flow.

Information about the interaction between a closing fracture and void space evolution can be gleaned from crack closure experiments (e.g. Brantley et al., 1990; Hickman and Evans, 1992; Beeler and Hickman, 2004). During closure, fluid-filled voids compete for space with the asperities. As closure continues the voids may form elongated tubules over time that might become isolated from the larger fluid network (forming bubble trains). These isolated fluid inclusions can no longer drain and relieve fluid pressure. Further closure of the fracture will raise fluid pressures in the isolated inclusion, potentially leading to frictional failure of the fracture.

Such a process may be responsible for the residual seismicity often reported after shut-in of injection wells (e.g. Baria et al., 2005). However, other mechanisms may operate in geothermal systems (e.g. time-dependent stress corrosion at crack tips; delayed fluid percolation through the reservoir; Coulomb stress transfer of previously ruptured fractures; alteration of strength properties due to mineral diagenesis) and any combination of these mechanisms may explain the field observations. For example, post shut-in seismicity may relate to other parameters that can influence deformation – such as time, fluid-rock chemical interaction, and loading (or stressing) conditions.

Mechanical rate effects

Cao and Aki (1986) extended the work of Kanamori and Allen (1986) by considering the catalog of earthquake stress drop data in terms of average slip rate across the fault. They noted that the amplitude of earthquake stress drop generally decreased as the average slip rate across the fault increased, an observation they subsequently modeled using existing rate- and state-dependent friction relations.

Similar rate effects have been reported from laboratory experiments on bare rock surfaces (e.g. Wong and Zhao, 1990; Karner and Marone, 2000). Stick-slip data obtained from granite blocks sheared in the biaxial testing configuration show systematic trends (Karner and Marone, 2000; see Fig. 2). First, the average amplitude of stress drop generally decreases with faster loading rates (see the peak to peak amplitudes in Figure 2a and the average trend

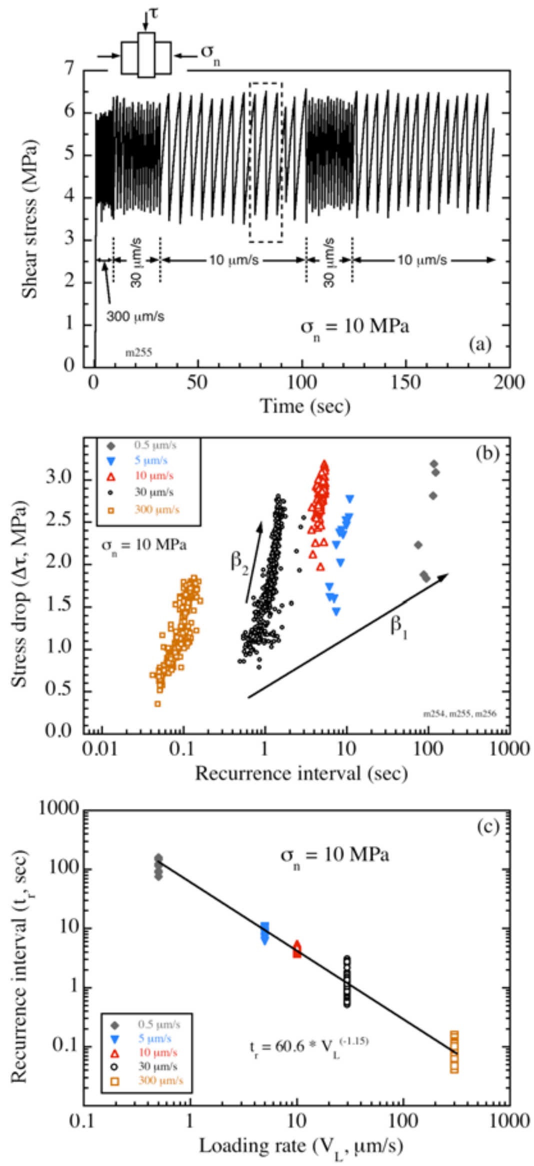

Figure. 2. Results from double-direct shear tests on granite blocks (after Karner and Marone, 2000). a) Normal stress (σ_n) was held constant at 10 MPa while the center block was loaded at the rates shown. After yield, repetitive stick-slip events occurred with recurrence times and amplitudes that varied with loading rate. b) Stress drop values for instabilities as a function of the time since the end of the last event. Data show two distinct trends (a rate effect, β_1 and an aging effect, β_2). c) Recurrence interval scales with loading rate via a power-law relationship.

denoted by β_1 in Figure 2b). Second, the recurrence time between successive events decreases with increasing loading rate via a power-law relationship (see Figure 2c and the close spacing of events at faster velocities in Figure 2a). Third, for any given loading rate the amplitude of stress drop increases with the time since the previous event (see β_2 in Figure 2b).

Karner and Marone (2000) showed that the results of their stick-slip shear tests, together with those of Wong and Zhao (1990) and the theoretical development of Beeler et al. (2001), indicate that stress drop scales with both recurrence time and loading rate via the relation:

$$\Delta\tau = kV_L t_r \qquad \text{(Eq. 1)}$$

where *k* reflects the elastic stiffness of the shear zone.

These data clearly show two distinct rates of increase in stress drop (see β_1 and β_2 in Figure 2a). The velocity-dependent trend (β_1) is consistent with observations from natural faults (e.g. Cao and Aki, 1986). This suggests that lower stress drop amplitudes might be generated in geothermal systems by increasing the stressing rate during stimulation (e.g. via fluid pumping). Yet, this must be taken with caution as higher stressing rates will induce a larger number of events in a short time frame, a factor that may work against induced seismicity mitigation efforts.

The second trend (β_2) agrees with previous friction work documenting mechanical '*aging*' of a population of contacting asperities that can alter the strength of a shear zone over time (e.g. Dieterich, 1972). This restrengthening can arise from a number of mechanisms that involve deformation of asperities influenced by the in-situ physical, thermal and chemical conditions – processes that likely operate within geothermal systems. Such aging effects will likely influence the strength properties of geothermal fractures, an issue that could have bearing on the productivity of the fracture network through the lifespan of an EGS field.

Mechanical aging effects

Li et al. (1998) reported on repeat seismic surveys of the main fault that ruptured during the 1992 *Mw* 7.3 Landers earthquake. Their observations of P, S and fault zone trapped waves show decreased travel times within the years following the quake. Most importantly, this travel time reduction was significant within ~200 meters normal to the rupture zone. By correlating their observations to laboratory data, Li et al. (1998) interpreted their data in terms of time-dependent restrengthening (healing) of the fault zone.

Such healing effects may reflect mechanical deformation of asperities and growth of total contact area of the shear surface – in a manner consistent with the β_2 trend shown in Figure 2a. In the case of mature fault zones with a cataclastic core (gouge), similar growth in real area of contact may occur via consolidation of the granular gouge.

Laboratory experiments investigating healing in fault gouge typically involve loading conditions that are close to those needed for steady-state sliding (see Figure 3a). To initiate mechanical healing, loading is typically stopped for a prescribed interval of time (hold). During holds, stress decays exponentially due to continued slip within the gouge that is associated with layer compaction. Upon reloading after holds, stress increases to a peak level before subsequently returning to steady-state levels. The difference between steady-state friction and the peak friction on reload ($\Delta\mu$) is taken as a measure of restrengthening.

For room temperature shear of quartz sand (Figure 3, after Karner et al., 2005) frictional healing is noted to increase with the logarithm of hold time. These experiments also show that the amplitude of both stress relaxation and layer compaction increase with hold time. These data suggest that shear-enhanced consolidation of the gouge layer serves to strengthen the layer. Furthermore, these processes display time-dependent behavior that can be modeled using existing friction constitutive laws (see Marone, 1998, for a review). Greater complexity of the observed trends related to healing during holds has been documented as functions of large perturbations in normal stress (e.g. Richardson and Marone, 1999) and shear stress (e.g. Karner and Marone, 2001).

Assuming fractures and small faults in geothermal systems are close to the critical stress needed for shear failure, then the laboratory results best suited for describing the temporal evolution of fracture strength will be of the sort presented in Figure 3. That is, experiments that mimic the small load perturbations at conditions close to that needed for failure. However, if large volumes and/or pressures of stimulation fluid are required to initiate failure then the fracture network may not resemble a critically stressed system. In such a case, the experiments that explore the effects of larger stress perturbations will be more relevant. Hence, direct application of healing trends derived from laboratory data will require an understanding of the stress state within the geothermal system. Adding to the complexity, the hot and aqueous conditions of EGS reservoirs will serve to promote fluid-rock interactions. Such diagenetic reactions can have dramatic effects on fracture and frictional strength as well as fluid transport properties. Here again, the laboratory provides a venue to explore these issues.

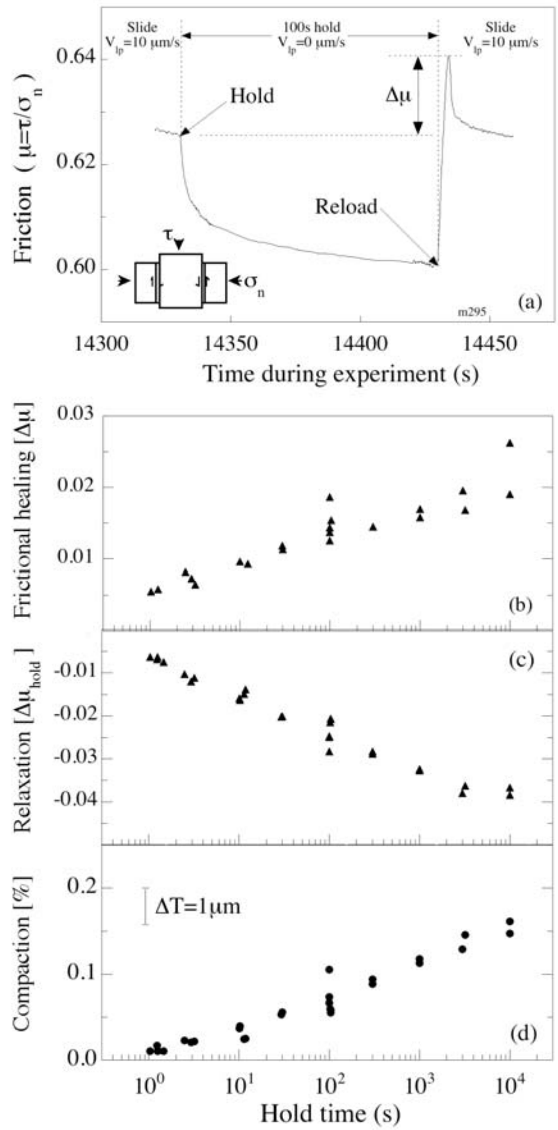

Figure. 3. Results from stress relaxation tests on layers of quartz sand (after Karner et al., 2005). a) Room temperature/humidity tests performed in double-direct shear configuration at constant normal stress of 25 MPa. Friction is calculated as the ratio of shear and normal stresses. Holds are initiated by setting the imposed loading rate to zero. The difference ($\Delta\mu$) between reload peak friction and steady-state sliding level is taken as a proxy for frictional healing. b) Healing increases with log of hold time. c) Amplitude of stress relaxation during a hold increases with log hold time. d) Layer compaction during holds increases with log hold time.

Hydrothermal effects on strength

Karner et al. (1997) performed shear experiments on quartz powder layers under hydrothermal conditions (confining pressure 250 MPa, distilled water as pore fluid with pressure 75 MPa). They performed a suite of tests whereby the powder layers were annealed at elevated temperature (to 636 °C) prior to deformation at 230 °C. For constant annealing time, their results showed that strength of the layer increased linearly with the annealing temperature. They interpreted these data to indicate that greater annealing temperatures permit more silica to enter into solution, silica that is reprecipitated as cement when temperature is reduced to 230 °C for deformation. For constant annealing temperature, they observed that the layer strength increased with the logarithm of healing time. These data suggest that strength of faults and fractures is strongly controlled by the kinetics of the diagenetic reactions.

Karner et al. (1997) also performed stress relaxation tests (similar to those shown in Figure 3) at temperatures to 636 °C. Healing data were subsequently presented as a function of deformation temperature by Karner (2005) and compared to previous results from friction tests on granitic powder layers (Blanpied et al, 1998; see Figure 4). While the healing rates show some scatter as a function of increasing temperature, the data suggest that healing rates vary systematically with increasing temperature. At comparatively low temperatures (less than 300 °C) the healing rates show a tendency to increase with temperature. Above 300 °C the healing rates tend to decrease with increasing temperature and are negative at the highest temperatures. These results may reflect the competition between solution transfer processes (e.g. dissolution, pressure solution) and precipitation (e.g. cementation). At the lower temperatures, greater hold times favor the generation of cements formed by precipitation of the dissolved ionic content in the pore fluids. At the higher temperatures, however, dissolution processes may be the kinetically dominant process thereby promoting solution transfer assisted creep of the shear zone (hence, not allowing strong cements to form).

As existing geothermal reservoirs are typically at temperatures lower than 350 °C, then the results shown in Figure 4 suggest that fractures will regain their strength (likely due to cementation) during the exploitable lifetime of the reservoir. This will have bearing on stimulation activities performed years after the reservoir starts producing. However, the precipitation of pore-filling cements will also have significant impact on the fluid transport properties of the fracture network.

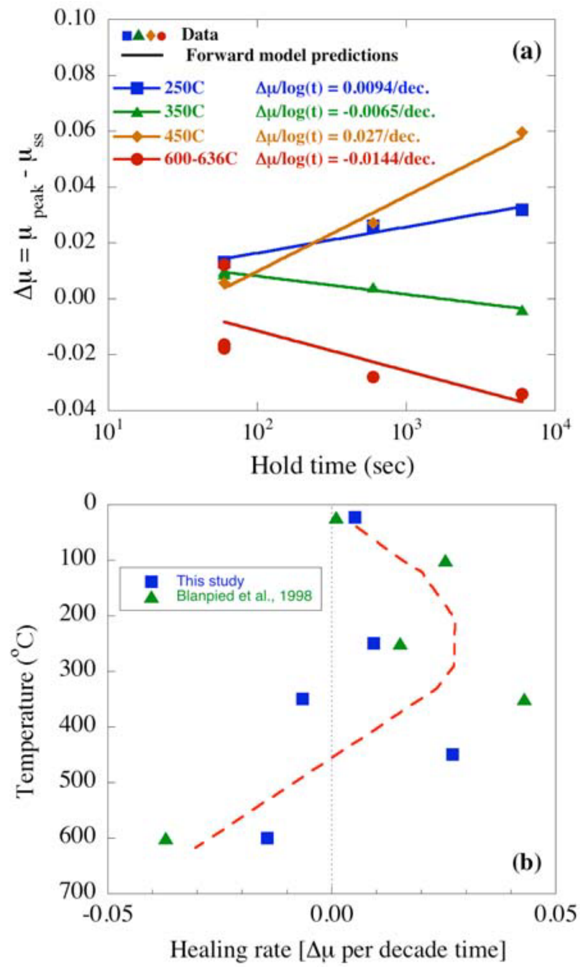

Figure. 4. Results from stress relaxation tests on layers of quartz sand (after Karner et al., 1997; Karner, 2005) and similar tests on granitic powder layers (Blanpied et al., 1998). a) Healing values for quartz layers were determined from stress relaxation data, in a manner similar to that shown in Figure 3. Rates of healing ($\Delta\mu$ / log t) vary considerably with the temperature at which deformation occurs. b) Healing rates from (a) are plotted together with data from Blanpied et al. (1998). While there is some scatter, the data suggest that healing rates increase with temperature to ~300 °C. At temperatures above ~300 °C, healing rates systematically decrease.

Hydrothermal effects on fluid flow

Olsen et al. (1998) performed shear experiments on layers of granular feldspar and quartz under hydrothermal conditions (confining pressure 60 MPa, deionized pore fluid at pressure of 10 MPa, temperatures to 250 °C). Their experiments were similar to the stress relaxation tests of Karner et al. (1997) except that they flowed pore fluid through the shear zone during deformation, thereby continuously monitoring permeability. During their hold cycles (up to 2 days), frictional strength evolved in a manner similar to that described above (see Figures 3-4). Permeability progressively decreased during holds and subsequently increased when loading was restated after holds (similar to previous observations of Karner and Schreiber, 1993). Healing values and permeability reduction (sealing) were determined for each hold and did not show a clear systematic trend as a function of hold time or temperature. However, Olsen et al. (1998) observed a distinct positive correlation between the amount of healing and sealing that occurred during holds. When coupled with microstructural analyses, these data suggest that diagenesis of feldspars (in the form of dissolution and precipitation of cements) served to indurate the shear zone (heal) and clog up the flow network (seal).

As the time frame of laboratory experiments is typically short (minutes to weeks), the combined results from laboratory tests indicate that hydrothermal diagenesis should markedly alter the mechanical and fluid transport properties of fractures in geothermal systems. Clearly, the fracture network will have both spatial and temporal components to the evolution of these properties. The evolution of fluid transport properties can be assessed by coupling information gleaned from laboratory experiments to data from repeat tracer tests, wellbore injection volumes and flow rates, and chemical analysis of subsurface fluids. The evolution of mechanical properties can be assessed if repeat stimulations are performed on the reservoir, or by comparing to the microseismicity that occurs within the reservoir.

Coupling laboratory strength data to seismicity

In a recent study, Peng et al. (2005) presented an analysis of seismicity on the Calaveras Fault in California. In particular, Peng et al. (2005) concentrated on seismic multiplets that were readily identifiable as repeat earthquakes (events that continuously rupture the same patch of the fault). They analyzed 194 clusters of repeating earthquakes and considered the evolution of seismic moment data as functions of event recurrence time and depth within the fault. In that way, they could assess the time-dependence of seismic moment in terms of healing rates and then compare these rates at various depths. Despite exhibiting some scatter, their data showed healing rates that progressively decreased with increasing depth. In an effort to constrain the mechanical processes involved, they compared this depth-dependent healing rate trend to results from room-temperature shear experiments on quartz gouge layers (Karner and Marone, 1998 and 2001) and the hydrothermal shear tests of Karner et al. (1997).

While the mechanical interpretations of the Calaveras Fault data (Peng et al., 2005) may not be unique, subsequent field information that is gathered may help better understand the spatio-temporal evolution of such fault zones. It is expected that the quantity of field information collected from natural systems is less than that which can be obtained from geothermal systems. As such, if the approach of Peng et al. (2005) were applied to geothermal systems then laboratory-based interpretations of geothermal fracture network evolution may be much better constrained than their natural counterparts. Hence, coupling laboratory observations to field measurements can potentially be of great value to the creation and maintenance of fractures in geothermal reservoirs – as well as mitigation of problems (such as induced seismicity).

Summary

This paper presents results from laboratory experiments that can provide insights about the spatial and temporal evolution of fracture properties in geothermal reservoirs. Such observations are increasingly being compared directly to field measurements from natural fault systems. As the data collected at exploitable geothermal fields is typically more extensive than natural faults, it is expected than laboratory-based interpretations of mechanical and fluid transport properties can be better constrained when applied to geothermal systems.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Geothermal Technology, under DOE Idaho Operations Office Contract DE-AC07-05ID14517, whose support is gratefully acknowledged.

REFERENCES

Baria, R., S. Michelet, J. Baumgaertner, B. Dyer, A. Gerard, T. Hettkamp, D. Teza, N. Soma, H. Asanuma, and J. Garnish (2005), “Creation and Mapping of 5000 m deep HDR/HFR Reservoir to Produce Electricity”, *Proceedings of the World Geothermal Congress*, Antalya, Turkey, 24-29 April 2005.

Beeler, N.M. and S.H. Hickman (2004), "Stress-induced, time-dependent fracture closure at hydrothermal conditions", *Journal of Geophysical Research*, **109** (B2): Art. No. B02211.

Beeler, N.M., S.H. Hickman, and T-f. Wong (2001), "Earthquake stress drop and laboratory-inferred interseismic strength recovery", *Journal of Geophysical Research*, **106**, 30701-30713.

Blanpied M.L., C.J. Marone D.A. Lockner, J.D. Byerlee and D.P. King (1998), "Quantitative measure of the variation in fault rheology due to fluid-rock interactions", *Journal of Geophysical Research*, **103**: 9691-9712.

Brantley, S.L., B. Evans, S.H. Hickman, and D.A. Crerar (1990), "Healing of microcracks in quartz: implications for fluid flow", *Geology* **18**, 136-139.

Cao, T. and K. Aki (1986), "Effect of slip rate on stress drop", *Pure and Applied Geophysics*, **124**. 515-529.

Cuenot N., J. Charléty, L. Dorbath, and H. Haessler, (2005), "Faulting Mechanisms and Stress Tensor at the European HDR Site of Soultz-Sous-Forets," *Proceedings of the 30th Workshop on Geothermal Reservoir Engineering*, Stanford Univ., Stanford CA, Jan 31-Feb 2 2005.

Dieterich, J.H. (1972), "Time-dependent friction in rocks", *Journal of Geophysical Research*, **77**, 3690-3697.

Fehler, M., A. Jupe, and H. Asanuma (2001), "More Than Cloud: New technologies for characterizing reservoir structure using induced seismicity", *The Leading Edge (SEG)*, **20**, 324-328.

Healy, D., R.R. Jones, and R.E. Holdsworth (2005), "Three-Dimensional Brittle Shear Fracturing by Tensile Crack Interaction", *Eos. Transactions AGU* 86(52) Fall Meet. Supplement (2005) Abstract T23B-0548.

Hickman, S., and B. Evans (1992), "Growth of grain contacts in halite by solution transfer: Implications for diagenesis, lithification, and strength recovery", in *Fault Mechanics and Transport Properties of Rocks*, edited by B. Evans and T.-F. Wong, pp. 253-280, Academic, San Diego, Calif.

Kanamori, H., and C.R. Allen (1986), "Earthquake repeat time and average stress drop", In: Das, S., Boatwright, J., Scholz, C.H. (Eds.), Earthquake Source Mechanics. *A.G.U. Geophysical Monograph* **37**. 227-235.

Kanamori, H. and D. Anderson (1975), "Theoretical basis of some empirical relations in seismology", *Bulletin of the Seismological Society of America*, **65**, 1073-1095.

Karner, S.L. (2005), "What can granular media teach us about deformation in geothermal systems?", *Proceedings of the 40th U.S. Symposium on Rock Mechanics (USRMS)*, Paper 05-797, Anchorage Alaska (June 25-29, 2005).

Karner, S.L., F.M. Chester, and J.S. Chester (2005), "Towards a General State-variable Constitutive Relation to Describe Granular Deformation", *Earth and Planetary Science Letters,* **237**, 940-950.

Karner, S.L. and C. Marone (1998), "The effect of shear load on frictional healing in simulated fault gouge", *Geophysical Research Letters*, **25**, 4561-4564.

Karner, S.L. and C. Marone (2000), "Effects of loading rate and normal stress on stress drop and stick-slip recurrence interval", *A.G.U. Monograph 120*: GEOCOMPLEXITY AND THE PHYSICS OF EARTHQUAKES, Editors J.B. Rundle, D.L. Turcotte, W. Klein, 187-198.

Karner, S.L. and C. Marone (2001), "Frictional restrengthening in simulated fault gouge: Effect of shear load perturbations", *Journal of Geophysical Research*, **106**, 19319-19337.

Karner, S.L., C. Marone, and B. Evans (1997), "Laboratory study of fault healing and lithification in simulated fault gouge under hydrothermal conditions", *Tectonophysics*, **277**, 41-55.

Karner, S.L., and B.C. Schreiber (1993), "Experimental Simulation of Plagioclase Diagenesis at P-T Conditions of 3.5km Burial Depth", *Pure and Applied Geophysics*, 141, 221-247.

Kellogg L.H., B.H. Hager, and R.D. van der Hilst (1999), "Compositional stratification in the deep mantle", *Science*, **283,** 1881-1884.

Kostrov, B. (1974), "Seismic moment and energy of earthquakes, and seismic flow of rock", *Izv. Acad. Sci. USSR Phys. Solid Earth*, **1**, 23-40.

Li, Y-g., J.E. Vidale, K. Aki, F. Xu, and T. Burdette (1998), "Evidence of shallow fault zone strengthening after the 1992 M7.5 Landers, California, earthquake", *Science*, **279,** 217-219.

Lockner, D.A., J.D. Byerlee, V. Kuksenko, A. Ponomarev, and A. Sidorin (1991), "Quasi-static fault growth and shear fracture energy in granite", *Nature*, **350**, 39-42.

Marone, C. (1998), "Laboratory-derived friction laws and their application to seismic faulting", *Annual Reviews of Earth and Planetary Sciences*, **26**, 643-696.

Marone, C., J.E. Vidale, and W.L. Ellsworth (1995), "Fault healing and time dependent variations in source properties of repeating earthquakes", *Geophysical Research Letters*, **22**, 3095-3098.

Olsen M.P., C.H. Scholz, and A. Léger (1998), "Healing and sealing of a simulated fault gouge under hydrothermal conditions: Implications for fault healing", *Journal of Geophysical Research*, **103**, 7421-7430.

Pacheco, J.F. and L.R. Sykes (1992), "Seismic moment catalog of large shallow earthquakes, 1900 to 1989", *Bulletin of the Seismological Society of America*, **82**, 1306-1349.

Peng, Z-g., J.E. Vidale, C. Marone, and A. Rubin (2005), "Systematic variations in recurrence interval and moment of repeating aftershocks", *Geophysical Research Letters*, **32**, Art. No. L15301.

Richardson, E. and C. Marone (1999), "Effects of normal stress vibrations on frictional healing", *Journal of Geophysical Research*, **104**, 28859-28878.

Wald, D.J. and T.H. Heaton (1994), "Spatial and temporal distribution of slip for the 1992 Landers, California, earthquake", *Bulletin of the Seismological Society of America*, **84**, 668-691.

Wong, T-f. and Y. Zhao (1990), "Effects of loadpoint velocity on frictional instability behavior", *Tectonophysics*, **175**,177-195.